NITRATE AND NEBRASKA'S SMALL COMMUNITY AND RURAL DOMESTIC WATER SUPPLIES: AN ASSESSMENT OF PROBLEMS, NEEDS AND ALTERNATIVES

APPENDIX II

BACKGROUND INFORMATION ON TREATMENT METHODS AND DISTRIBUTION SYSTEMS

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Acronyms, Abbreviations, Formulas, and Terms

ADF	average daily flow		MCL	maximum contaminant level
BAT	best available technology		MF	microfiltration
BLS	Bureau of Labor Statistics		mg/L	milligram(s) per liter
DBP	disinfection byproducts		NF	nanofiltration
ED	electrodialysis		O&M	operations and maintenance
EDR	electrodialysis reversal		PDF	peak daily flow
ENR	Engineering News Record		POU	point of use
EPA	US Environmental Protection Agency		RO	reverse osmosis
			SDWA	Safe Drinking Water Act
GAC	granular activated carbon		SLR	surface loading rate
GPCD	gallons per capita per day		SWTR	Surface Water Treatment Rule
GPM	gallons per minute		TDS	total dissolved solids
GPD	gallons per day		TSS	total suspended solids
IX	ion exchange		UF	ultrafiltration
LOTW	locally owned treatment works		WTP	water treatment plant

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Al^{+3}	aluminum ion		HCO_3^-	bicarbonate ion
Ba^{+2}	barium ion		H_2O	water
Ca^{+2}	calcium ion		H_2SO_4	sulfuric acid
$CaCO_3$	calcium carbonate		HPC	heterotrophic plate count
$Ca(OH)_2$	calcium hydroxide (hydrated lime)		Na^+	sodium ion
Cl^-	chloride ion		Na_2CO_3	sodium carbonate (soda ash)
Cl_2	chlorine		Ni^{+2}	nickel ion
ClO_2	chlorine dioxide		NO_3^-	nitrate ion
Fe^{+2}	ferrous ion		O_3	ozone
Fe^{+3}	ferric ion		SiO_2	silica
H^+	hydrogen ion		SO_4^{-2}	sulfate ion

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Blending - mixing of desalted water with un-desalted water to obtain the following advantages: the addition of hardness and alkalinity from undesalted water helps to reduce the corrosivity of the product water; the amount of post-treatment chemical and the water treatment plant size are reduced, thereby lowering capital and operating costs.

Concentrate (or brine) - the salt waste stream produced as a by-product of RO or nanofiltration treatment of water containing salts.

Electrodialysis - a water treatment process that removes dissolved salts from water using a direct current electrical potential.

Electrodialysis reversal - an automatic operating feature of some ED units that reverses the electrical potential applied to the two electrodes, about every 15 minutes, to promote cleaning of the unit.

Locally owned treatment works - the facility that accepts and treats the community's wastewater.

Membrane selectivity - the ability of a membrane to selectively remove certain ions over others by being composed of selectively charged ionic groups.

Nanofiltration - a selective form of reverse osmosis that has a lower rejection rate for monovalent ions than multivalent ions, and thus, can operate at significantly lower operating pressures than RO membranes.

Permeate - the product water from a desalting process

Pretreatment - treatment units located upstream of a desalting process necessary to remove compounds that are detrimental to the membranes and which would shorten the life of the desalter.

Recovery - the amount of product water attainable, expressed as a percent of the feed flow.

Rejection - the rate at which an ion is removed, expressed as a percent.

Reverse osmosis - the process of applying to water that is in contact with a semi-permeable membrane, a pressure in excess of its osmotic pressure, so that clean water permeates through the membrane and ions in the water do not pass through the membrane, but are collected separately.

Silt density index - a measure of the fouling potential of the feed from colloidal-size materials.

TREATMENT METHODS

General

Nitrate(s) (NO_3^-) are inorganic anions, whose oxidation state is elemental nitrogen gas, with a molecular weight 62.00. NO_3^- are often attached to other particles, including other NO_3^-, which increases the total molecular weight of the particle. NO_3^- are water-soluble, colorless, odorless, and tasteless. NO_3^- is a macro-nutrient that is an essential part of proteins manufactured by bacteria and algae in water.

Nitrogen is a naturally occurring gas in the earth's atmosphere, at approximately 78 percent by volume. NO_3^- are naturally occurring nitrogen-oxygen compounds which combine with various organic and inorganic compounds in both water and plants. Natural sources of NO_3^- in waters include direct fixation of nitrogen gas by algae and bacteria, photochemical fixation, electrical discharge, and oxidation of ammonia and nitrite by nitrifying bacteria. NO_3^- are used by bacteria to form amino acids used in the synthesis of proteins for all plants and animals. Elevated levels of NO_3^- in today's surface and groundwaters are a result of overuse of nutrient-rich chemical fertilizers, municipal and industrial wastewaters, refuse dumps, and improper disposal of human and animal wastes.

Nitrate is a regulated primary contaminant of the Safe Drinking Water Act (SDWA). Primary contaminants have been shown to adversely affect human health and welfare. Contaminants identified as secondary in the SDWA have been found to affect aesthetics, such as taste, odor, or color. The maximum contaminant level (MCL) for NO_3^- , expressed as nitrogen, is 10 mg/L (for NO_3^- as Nitrate, the MCL is 45 mg/L).

The health effects of excessive NO_3^- include methemoglobinemia (blue baby syndrome resulting in oxygen deprivation in infants under 6 months), and is generally considered a concern for children under age 5. The infant's immature digestive system converts the relatively harmless nitrate into nitrite which in turn combines with some of the hemoglobin in the blood to form methemoglobin, which cannot transport oxygen. The ailment in rare, but can result in brain damage or death. Older children and adults are generally only susceptible if they also experience enzyme or erythrocyte metabolism deficiency, chronic anemia, or gastric diseases. Pregnant women can also be susceptible to methemoglobinemia.

Nitrate ions are not easily filtered. The US Environmental Protection Agency (EPA) has recognized only three water treatment unit processes as best available technology (BAT) treatment techniques for NO_3^- removal. These BATs are ion exchange (IX), reverse osmosis (RO), and electrodialysis (ED). Nanofiltration (NF), a membrane filtration process similar to RO, uses ion specific membranes to remove NO_3^-. Point of use (POU) devices using RO, NF, distillation, and IX can also be used to remove NO_3^-. Others have found that NO_3^- can be removed using either chemical or biological denitrification: either above ground in tanks or wetlands (ex-situ treatment) or below ground in the soil/water matrix (in-situ treatment). These latter treatment techniques may meet a community's needs in terms of treatment however, they are not commonly used and data confirming their reliability and cost are not easily found. For these reasons, the EPA BATs are emphasized in this report.

Ion Exchange

General Description. — IX is a reversible chemical process in which ions from an insoluble, permanent, solid resin bed are exchanged for different ions in the feed water. The process relies on the fact that water solutions must be electrically neutral, therefore ions in the resin bed are exchanged with ions of similar charge in the water. As a result of the exchange process, no reduction in ions is obtained. In the case of NO_3^-, operation begins with a fully recharged resin bed, having enough Cl^- or OH^- ions to carry out the anion exchange. Usually polymer resin bed is composed of millions of medium sand grain size, spherical beads. As water passes through the resin bed, the Cl^- or OH^- anions are released into the water, being substituted or replaced with NO_3^- anions (ion exchange). When the resin becomes exhausted of Cl^- or OH^- ions, the bed must be regenerated by passing a strong, usually NaCl (or KCl), solution over the resin bed, displacing the NO_3^- ions with Cl^- ions. Current resins are not completely NO_3^- selective and may remove other anions, such as SO_4^{-2}, before removing the nitrate compounds. Therefore, NO_3^- ion exchange requires careful consideration of the complete raw water characteristics. Typically, NO_3^- ion exchange utilizes a Cl^- or OH^-, strongly basic anion resin bed.

Small Nebraska systems currently using this process include Adams, Hardy, Page, and a mobile home court in the Columbus area.

Pretreatment. — Guidelines for pretreatment are available on accepted limits for pH, organics, turbidity, and other raw water characteristics. Pretreatment may be required to reduce excessive amounts of TSS which could plug the resin bed, and typically includes media or carbon filtration.

Maintenance. — Depending on raw water characteristics and NO_3^- concentration, the resin will require regular regeneration with a NaCl solution. Preparation of the NaCl solution is required. Frequent monitoring is required to ensure nitrate removal. If utilized, filter replacement and backwashing will be required.

Waste Disposal. — Approval from local authorities is usually required for the disposal of concentrate from the regeneration cycle (highly concentrated NO_3^- solution); occasional solid wastes (in the form of broken resin beads) which are backwashed during regeneration; and if utilized, spent filters and backwash waste water.

Reverse Osmosis

General Description. — RO is a physical process in which contaminants are removed by applying pressure on the raw water to direct purer water through a semipermeable membrane. The process is the "reverse" of natural osmosis (water diffusion from dilute to concentrated through a semipermeable membrane to equalize ion concentration) as a result of the applied pressure to the concentrated side of the membrane, which overcomes the natural osmotic pressure. RO membranes reject ions based on size and electrical charge. The raw water is typically called feed; the product water is called permeate; and the concentrated reject is called concentrate. Common RO membrane materials include asymmetric cellulose acetate or polyamide thin film composite. Typical RO element configurations are shown on Figures 1 and

2. Common membrane construction includes spiral wound or hollow fine fiber. Each material and construction method has specific benefits and limitations depending upon the raw water characteristics and pretreatment. A typical RO installation includes a high pressure feed pump, parallel 1st and 2nd stage membrane elements (in pressure vessels); valving; and feed, permeate, and concentrate piping. All materials and construction methods require regular maintenance. Factors influencing membrane selection are cost, recovery, rejection, raw water characteristics, and pretreatment. Factors influencing performance are raw water characteristics, pressure, temperature, and regular monitoring and maintenance.
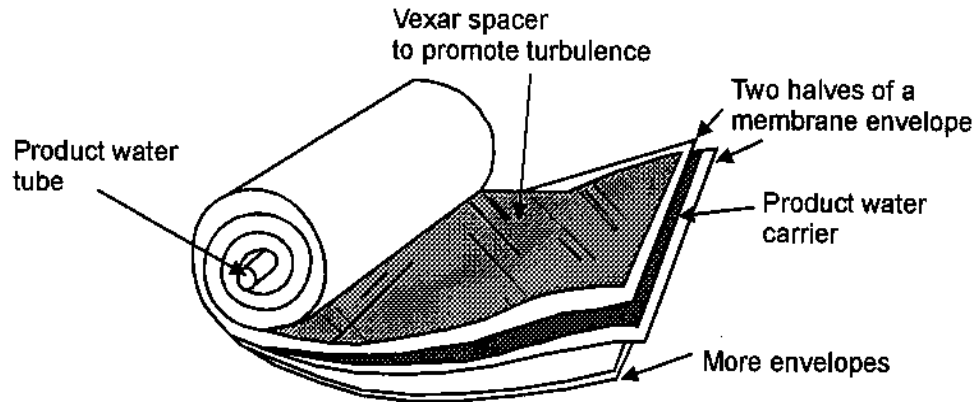
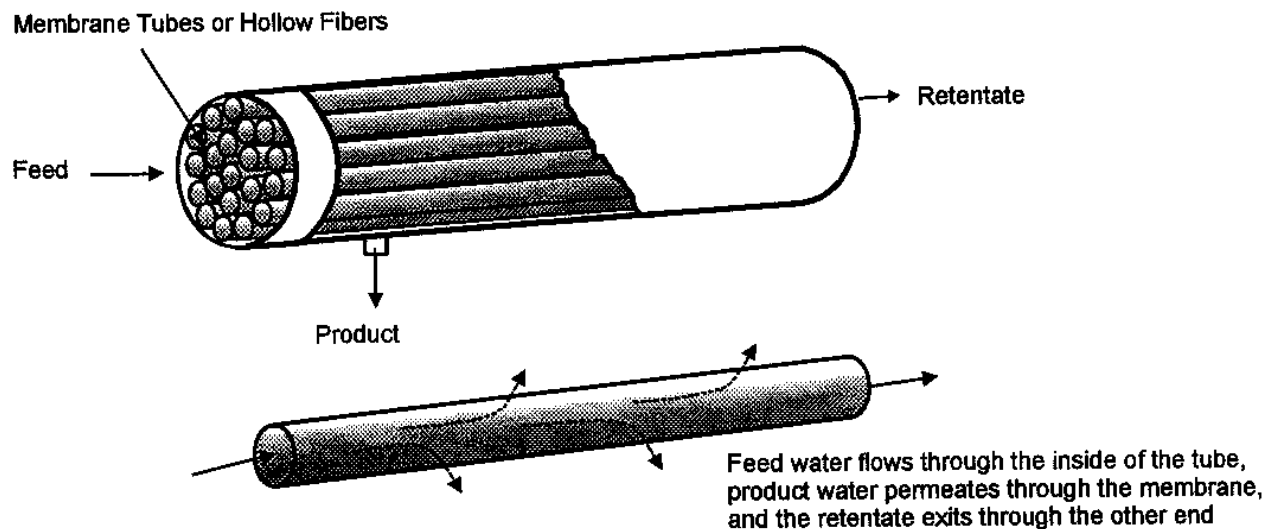**Figure 1. Spiral Wound Reverse-Osmosis Element.**

Figure 2. Tubular or Hollow Fiber Module.

Creighton and Elmwood are the two Nebraska small community systems currently using this process.

Pretreatment. — RO requires a careful review of raw water characteristics and pretreatment needs to prevent membranes from fouling, scaling, or other membrane degradation. Removal of suspended solids is necessary to prevent colloidal and bio-fouling, and removal of dissolved solids is necessary to prevent scaling and chemical attack. Pretreatment can include media filters to remove suspended particles; ion exchange softening or antiscalant to remove hardness; temperature and pH adjustment to lower chemical solubilities thereby preventing scaling; activated carbon or bisulfite to remove chlorine (post-disinfection may be required); and cartridge (micro) filters to remove some dissolved particles and any remaining suspended particles.

Maintenance. — Regular monitoring of membrane performance is necessary to determine fouling, scaling, or other membrane degradation. Use of monitoring equations to track membrane performance is recommended. Acidic or caustic solutions are regularly flushed through the system at high volume/low pressure with a cleaning agent to remove fouling and scaling. $NaHSO_3$ is a typical caustic cleaner. RO stages are cleaned sequentially. Frequency of membrane replacement depends on raw water characteristics, pretreatment, and maintenance.

Waste Disposal. — RO typically produces a concentrate flow stream of about 20 percent of the raw feed flow. Pretreatment waste streams, spent filters, and membrane elements all require approved disposal.

Nanofiltration

General Description. — NF is a physical process in which contaminants are removed by applying pressure on the raw water to direct purer water through a semipermeable membrane. NF is a selective form of RO that has a lower rejection rate for monovalent ions than multivalent ions, and thus, can operate at a significantly lower operating pressures than RO membranes. Like RO, NF membranes reject ions based on size. NF falls between RO and ultrafiltration (UF) on the filtration/separation spectrum. Materials, construction, and system installation of NF membranes are similar to RO.

Pretreatment, Maintenance, and Waste Disposal. — NF requirements are identical to RO. Since NF membranes are more specialized (target specific ions for removal) than RO membranes, their cost is higher but they can also be operated at much lower feed pressures. At large installations, NF is usually cheaper to operate than RO when life cycle costs are considered.

Electrodialysis

General Description. — ED is an electrochemical process in which ions migrate through an ion-selective semipermeable membrane as a result of their attraction to the electrically charged membrane surface. A positive electrode (cathode) and a negative electrode (anode) are used to charge the membrane surfaces and to separate contaminant particles into ions. The process relies on the fact that electrical charges are attracted to opposite poles. As a result of the removal process, reduction in ions (or TDS) is obtained. A common ED system includes a membrane

stack which layers several cell pairs, each consisting of a cation transfer membrane, a demineralized flow spacer, an anion transfer membrane, and a concentrate flow spacer. Typical ED configurations are shown on Figures 3 and 4. Electrode compartments are at opposite ends of the stack. The influent feed water (chemically treated to prevent precipitation) and concentrated reject flow in parallel across the membranes and through the demineralized and concentrate flow spacers, respectively. The electrodes are continually flushed to prevent fouling or scaling. Careful consideration of flush feed water is required. Typically, the membranes are cation or anion exchange resins cast in sheet form; the spacers are HDPE; and the electrodes are inert metal. ED stacks are tank contained and often staged. Membrane selection is based on careful review of raw water characteristics. A single-stage ED system usually removes 50 percent of the TDS; therefore, for water with more than 1000 mg/L TDS, blending with higher quality water or a second stage is required to meet 500 mg/L TDS.

Electrodialysis Reversal (EDR) uses the technique of regularly reversing the polarity of the electrodes, thereby freeing accumulated ions for cleaning. This process requires additional plumbing and electrical controls, but increases membrane life, does not require added chemicals, and eases cleaning.
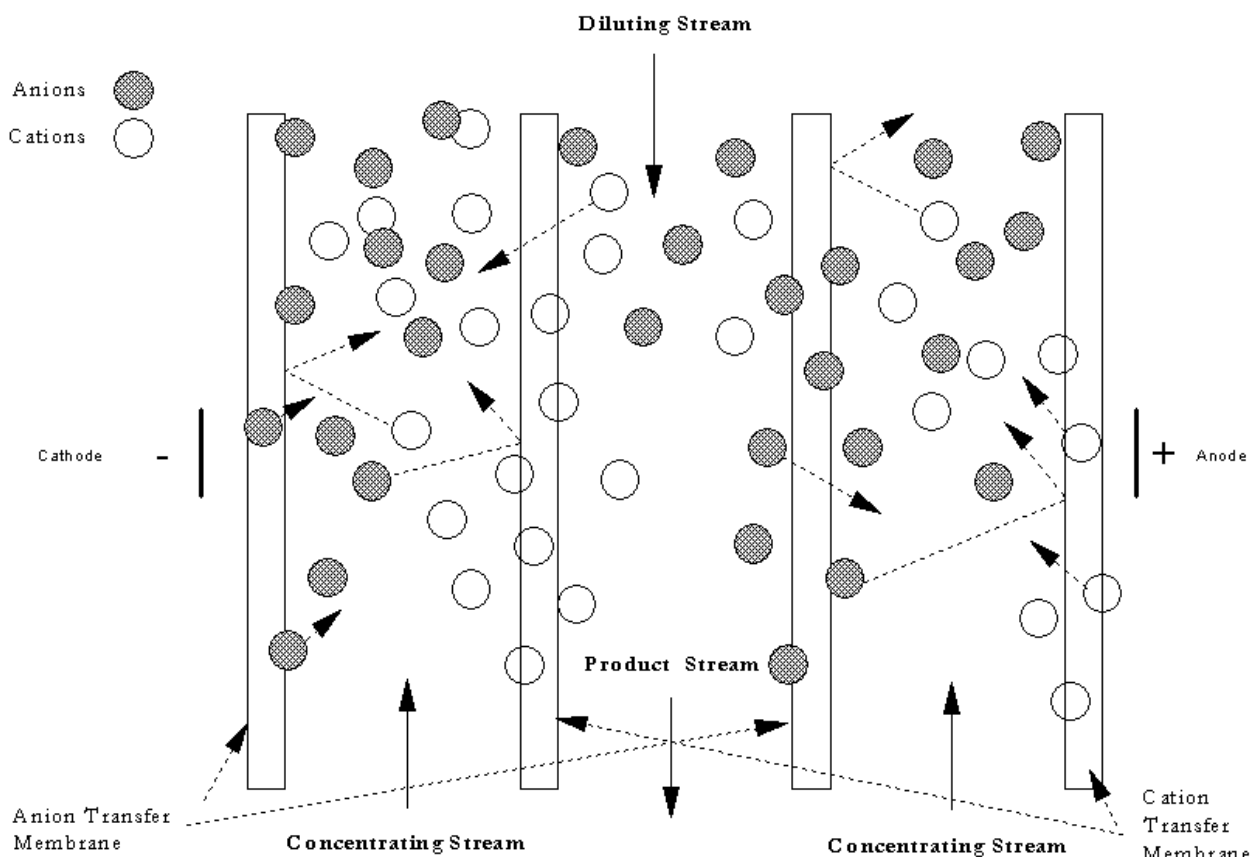

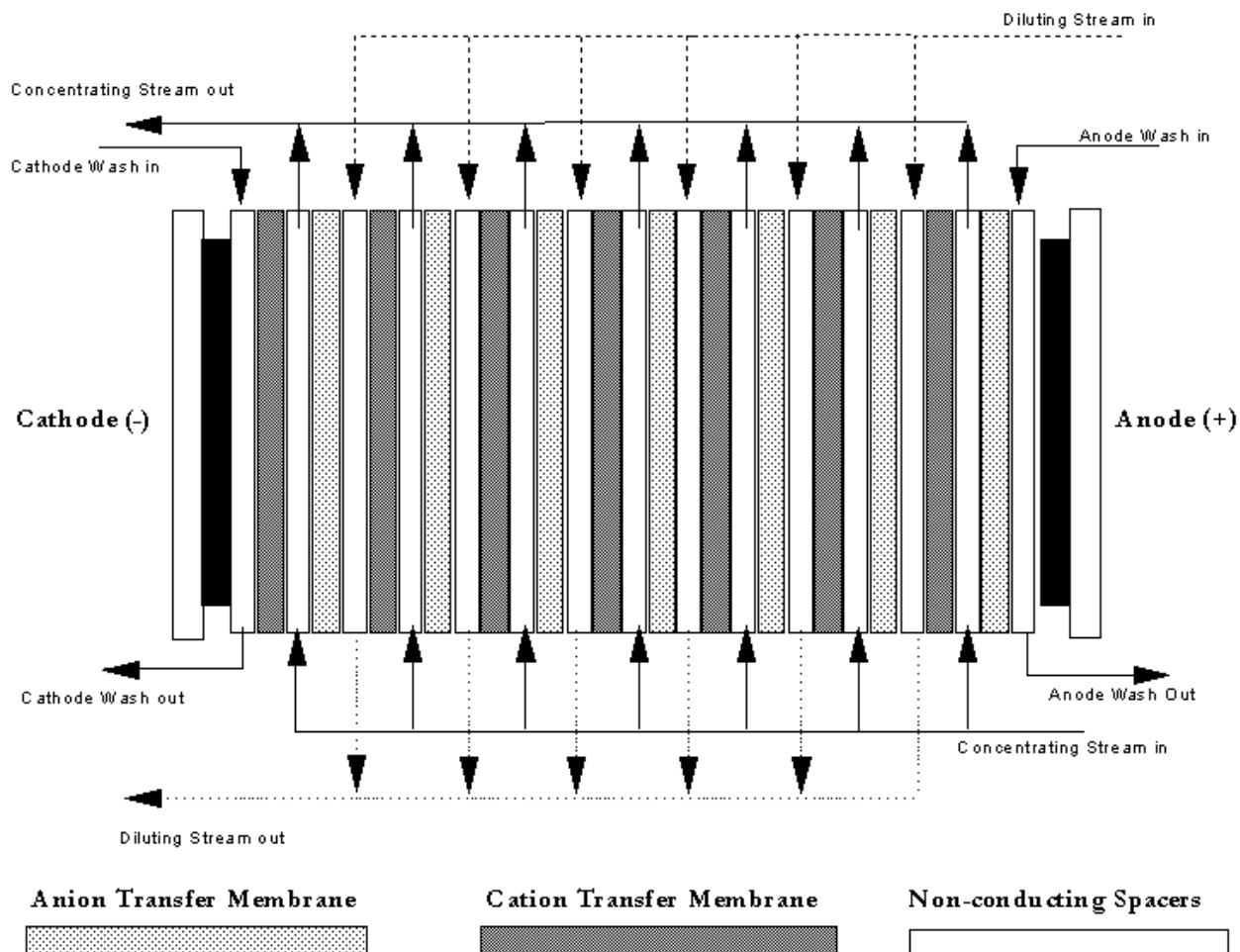**Figure 3. Transfer of Ions Within the Electrodialysis Stack**

Diluting Stream in

Concentrating Stream out

Cathode Wash in

Anode Wash in

Cathode (-)

Anode (+)

Cathode Wash out

Anode Wash Out

Concentrating Stream in

Diluting Stream out

Anion Transfer Membrane

Cation Transfer Membrane

Non-conducting Spacers

Figure 4. Flow Within the Electrodialysis Stack

Pretreatment. — Guidelines are available on accepted limits on pH, organics, turbidity, and other raw water characteristics. Typically requires chemical feed to prevent scaling, acid addition for pH adjustment, and a cartridge filter for prefiltration.

Maintenance. — ED membranes are durable, can tolerate pH from 1 - 10, and temperatures to 115°F for cleaning. They can be removed from the unit and scrubbed. Solids can be washed off by turning the power off and letting water circulate through the stack. Electrode washes flush out byproducts of electrode reaction. The byproducts are hydrogen, formed in the cathode space, and oxygen and chlorine gas, formed in the anode spacer. If the chlorine is not removed, toxic chlorine gas may form. Depending on raw water characteristics and NO_3^- concentration, the membranes will require regular maintenance or replacement. ED requires system flushes at high volume/low pressure; EDR requires reversing the polarity. Flushing is continuously required to clean electrodes. If utilized, pretreatment filter replacement and backwashing will be required.

Waste Disposal. — Highly concentrated reject flows, electrode cleaning flows, and spent membranes require approved disposal. Pretreatment processes and spent materials also require approved disposal.

Ex-Situ Denitrification

Denitrification processes are either chemical or biological where nitrate is reduced to nitrogen gas, nitrous oxide or is assimilated into the cellular stucture. Nonpathogenic bacteria can be used to denitrify water in a treatment system. The bacteria inhale NO_3^- and an organic carbon source and exhale inert carbon dioxide and nitrogen gases. However, the TOC concentrations found typically in groundwater are insufficient for the complete bacterial respiration. Therefore, for these types of biological denitrification processes, a carbon source such as ethanol, methanol, or acetic acid (vinegar) is needed.

In at least one case, a low-cost system using this process has been developed specifically for small communities. In that system, vinegar is added to the water before in enters the treatment reactors and bacteria consume the NO_3^- and vinegar. The water is pumped through the filters to remove the bacteria and waste products, which are flushed to the municipal sewage system. The town of Wiggins CO has recntly joined with Nitrate Removal Technologies, the company who commercialized this technology, to be the first community-based treatment system to demonstrate this technology.

In Germany, hydrogen is pumped into tanks and anaerobic bacteria convert nitrate to nitrogen gas through a process called "Denitropur". A full scale treatment plant has been in use since 1986.

In Belgium, studies continue on adding methanol to a fluidized bed system.

In-Situ Denitrification

Experiments have been made to treat nitrates below ground using chemical denitrification. Carried out by Dr. Spalding of UNL, in Merrick County NE, the testing started in 1993. By 2000, Dr. Spalding hopes to have the process refined and commercialized for use by small communities. Ethanol is injected into the nitrate laden groundwater to promote nitrate reduction.

Point of Use

POU devices are low flow water treatment units that can be installed under a sink, on a kitchen counter top, or on a home's main water supply line. They treat cold water by one or more specified technologies before supplying it to a dedicated outlet. The majority of POU systems utilize either RO, NF, distillation, or a disposable mixed-bed deionizer (IX). These processes can remove NO_3^- and other contaminants from water specifically for drinking and cooking purposes.

Reverse Osmosis. — Osmosis is a natural process in which a fluid passes through a semipermeable membrane from a lower concentration to a higher concentration in an attempt to equalize the concentrations. RO uses a separation process in which pressure is used to cause a flow through the membrane. Water is forced through the semipermeable membrane and dissolved solids are separated from it, concentrated, and collected in a reject flowstream. A RO system typically consists of three filter elements; a sediment filter (prefilter) to filter out coarse

solids, a semipermeable membrane, a carbon-cartridge (post-filter), and a water reservoir containing a pressurized rubber bladder with a dedicated faucet at the sink.

Distillation. — Distillation has historically been known to be highly effective in producing contaminant-free water. Water is first boiled in a chamber, causing steam to rise, leaving virtually all contaminants behind in the boiling chamber. Steam is collected and condensed into clean, distilled water. Depending on the system, impurities which remain in the chamber are automatically or manually flushed out.

Some distillation systems use particulate and adsorption filters as standard features to enhance the taste and reduce odors from storage tanks or piping. Most residential units use either air cooled or water cooled condensers. The air cooled units offer more advantages and are more popular because of their lack of wasted water.

Ion Exchange. — Most household water softening equipment on the market today use the IX principle. Hardness is caused by calcium and magnesium ions in the water. As hard water passes through a bed of IX medium, the hardness minerals are removed, leaving water soft. De-ionization is another IX process used to remove minerals from water. When the bed of medium is selected to remove negatively charged ions (NO_3^-), the process is called anionic exchange. Similarly, when a bed of resin medium is used to remove positively charged ions, the process is called cation exchange. Anion exchange is primarily used for the removal of very heavy minerals and NO_3^-. After continued use the bed of medium loses its ion transfer capability and must be "regenerated". This is done by flushing and rinsing the medium with a sodium chloride solution.

Types of Contaminants Each Alternative Addresses

Figure 5 provides information on the relative size of various materials in water and the separation processes required to remove them.

Ion Exchange

Anion IX medium can remove all single negatively charged ions including nitrate, sulfate, and chloride. IX cannot remove nonionic dissolved species or microbes. Recovery rates average over 95 percent when resins are properly "charged". The most common application of anionic
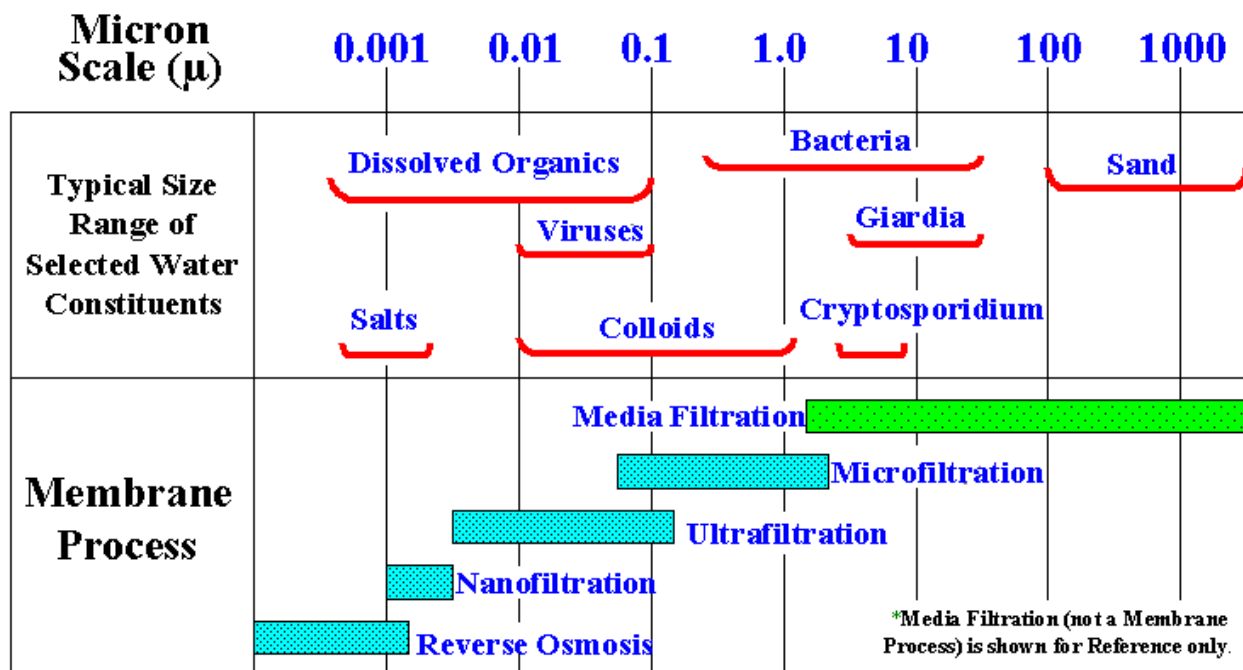
Figure 5. Sizes of Materials in Water.
(Taken from: Water Treatment Plant Design, AWWA & ASCE, Copyright 1998.)

IX is NO_3^- removal. If the water contains high levels of sulfates and chlorides, these anions will compete for transfer sites on the medium and lower the effectiveness to remove NO_3^-. Cation IX medium is effective in removing some metal/nonmetal ions, including iron and manganese. Some installations use two sets of IX tanks in series each containing both anion and cation medium. Some IX medium is capable of removing radioactivity. The medium then becomes radioactive and disposal must be in accordance with acceptable standards for radioactive material.

Reverse Osmosis

Of the basic membrane filtration methods (microfiltration (MF),UF, NF, and RO), RO removes the smallest particles, retaining substances smaller than 0.001 microns. RO removes particles down to a molecular weight of 100. Typical contaminant rejection rates range from 85 to 95 percent. RO is effective in removing sand, silt, clay, algae, protozoa (5 to 15 microns), bacteria (0.4 to 30 microns), viruses (0.004 to 6 microns), humic acids, organic/inorganic chemicals, and most aqueous salts and metal/nonmetal ions, including NO_3^-, iron, and manganese. Dissolved solids in water, primarily cations of calcium, magnesium, sodium, and potassium and anions of bicarbonate, chloride, nitrate, and sulfate are also removed. RO cellulose acetate membranes have been shown to remove herbicides to a 50 percent reduction level.

Nanofiltration

NF removes particles in the 0.001 to 0.1 micron range or in the 200 to 1,000 molecular weight range. Typical contaminant rejection rates range from 85 to 95 percent. NF membranes remove ions with divalent charges. Since calcium and magnesium, ions contributing to a waters hardness, are both divalent. NF membranes have received wide popularity as softening membranes, especially in Florida. Like RO, NF is effective in removing sand, silt, clay, algae, protozoa, bacteria, and some viruses, humic acids, organic/inorganic chemicals, aqueous salts, and metal/nonmetal ions, including NO_3^-, iron, and manganese. NF composite membranes have been shown to remove herbicides to a 99 percent reduction level.

Electrodialysis

ED is similar to RO in that it is capable of removing particles smaller than 0.001 microns, however, the particles must be charged ions. ED cannot remove nonionic dissolved species or microbes. Recovery rates for ED varies depending on the design and pretreatment options incorporated in the system, including concentrate recycle, product recycle, EDR or reversal frequency, electrode stream recycle, and chemical addition. ED is effective in removing humic acids and most aqueous salts and metal/nonmetal ions, including NO_3^-, iron, and manganese.

Ex-Situ Denitrification

The ability of these processes to remove other contaminants is limited by either the microbial population or the stoichiometric equations defining the denitrification reactions.   They therefore are not easily adaptable to removing other contaminants in the water and it has been found that when other anions, such as phosphate, sulfate, and chloride, exist in the water, they interfere with the nitrate removal process.

In-Situ Dentrification

Due to the limited use of in-situ treatment for nitrate removal, no data was found to support that this type of process can be used to remove other contaminants in the groundwater.

Point of Use

POU treatment units using the RO semipermeable membranes, like larger units, would remove most dissolved contaminants in water. These include primarily cations of calcium, magnesium, sodium, and potassium; and anions of bicarbonate, chloride, nitrate, and sulfate. POU distillation units can remove contaminants with an ionic charge. They can not remove nonionic pollutants such as suspended solids and bacteria.   POU IX units, like larger units, remove contaminants of similar charge. Competition from ions with similar ionic charge can reduce the ability of a unit to remove a specific contaminant.

Relative Construction Costs

Construction cost estimates for groundwater treatment plants (and annual operation and maintenance (O&M) costs and amortized costs) are presented for RO, NF, ED, and IX. The choice of which process to use and whether or not full compliance is achieved for both primary and secondary SDWA standards depends on specific well water quality. That is, a lower cost treatment process may be selected if the magnitude of a concentration of a secondary SDWA contaminant is determined to be tolerable.

Construction (and O&M) cost estimates are based on Reclamation's Water Treatment Estimation Routine cost program which utilizes cost curves prepared by the EPA. Input variables to the cost program include: the groundwater quality from Central Nebraska Basins (or for the surface water estimates, from USGS stations in the Platte River); and current indices from both the Bureau of Labor Statistics (BLS) and the Engineering News Record (ENR).

The cost estimates include all associated equipment for each unit process plus a 15 to 20 percent allowance for miscellaneous and contingency items, but do not include costs for land ownership, rights of way, special sitework, easements, or yard and offsite piping. Also not included are costs for an intake structure, grit removal equipment, or buildings for chemical feed and storage, administration, or a laboratory. Legal, administrative, and engineering costs for permitting, water quality monitoring, testing, and modeling are not included; nor are general contractor overhead and profit, fees for engineering, legal, and fiscal services, and interest during construction. For these reasons, the cost estimates found herein are valuable for a comparison of the various alternatives presented, but are not considered final construction cost estimates.

The basis for Reclamation's cost program is EPA's Research and Development manual numbered EPA-600/2-79-162a, and titled, "Estimating Water Treatment Costs" [Gumerman]. The cost program has been updated using documented improvements to the EPA database as well as, for RO and NF, a model prepared by Suratt. Each unit process is defined in terms of the following eight subcategories: excavation and sitework, concrete, steel, labor, pipe and valves, electrical equipment and instrumentation, and housing. These subcategories are linked to various cost indices and, for this report, have been updated to October 1997. Each unit's cost estimate includes a standby or spare unit.

Raw water pumping is not included because the pressure at the well may be sufficient to pump the water through the plant. Prechlorination using chlorine gas, for RO and NF, is added to destroy microorganisms found in the raw water. Post-chlorination, fed at 2 mg/L (and 3 mg/L for surface water), is added to provide final disinfection and to meet regulatory requirements of a chlorine residual in the distribution system.

Unit process construction costs for a groundwater treatment plant are presented in Table 1. Figure 6 is a graph of the complete treatment construction costs (without granular activated carbon (GAC)) versus flow for RO, NF, ED, and IX, and is based on a NO_3^- concentration of 15 mg/L. The complete treatment construction costs include a rapid rate, dual media (sand and anthracite) gravity filter and post-disinfection using chlorine. Costs for GAC are presented in Table 1, for those sites where herbicides and pesticides (Alachor and Atrazine) may be prevalent

due to agricultural practices, or bacteria and disinfection by-product (DBP) are a concern. Costs for the RO, NF, and ED are presented without a cost associated for brine disposal. This is because disposal to the local wastewater treatment plant is recommended and should not represent a large operating cost. Other cost assumptions for specific units are listed below. A typical groundwater treatment plant is shown schematically in Figure 7.

Table 1.
GROUNDWATER TREATMENT – CONSTRUCTION COSTS
[Assuming nitrate content of 1,000 mg/L in source water.
GAC = granular activated carbon]

Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Reverse Osmosis	$537,000	$648,000	$772,000
Dual media gravity filter	$223,578	$304,722	$379,607
Chlorine disinfection	$23,511	$24,654	$25,782
TOTAL w/o GAC	$784,089	$977,376	$1,177,389
GAC	$355,141	$516,508	$657,381
TOTAL w/ GAC	$1,139,230	$1,493,884	$1,834,770
Nanofiltration	$729,428	$847,373	$917,207
Dual media gravity filter	$223,578	$304,722	$379,607
Chlorine disinfection	$23,511	$24,654	$25,782
TOTAL w/o GAC	$976,517	$1,176,749	$1,322,596
GAC	$355,141	$516,508	$657,381
TOTAL w/ GAC	$1,331,658	$1,693,257	$1,979,977
Electrodialysis	$1,060,000	$1,290,000	$1,570,000
Dual media gravity filter	$223,578	$304,722	$379,607
Chlorine disinfection	$23,511	$24,654	$25,782
TOTAL w/o GAC	$1,307,089	$1,619,376	$1,975,389
GAC	$355,141	$516,508	$657,381
TOTAL w/ GAC	$1,662,230	$2,135,884	$2,632,770
Ion Exchange	$307,000	$500,000	$710,000
Dual media gravity filter	$209,295	$282,554	$350,058
Chlorine disinfection	$23,511	$24,654	$25,782
TOTAL w/o GAC	$539,806	$807,208	$1,085,840
GAC	$355,141	$516,508	$657,381
TOTAL w/ GAC	$894,947	$1,323,716	$1,743,221

Figure 6. Groundwater Treatment Construction Cost vs. Flow

Figure 6. Groundwater Treatment Construction Cost vs. Flow
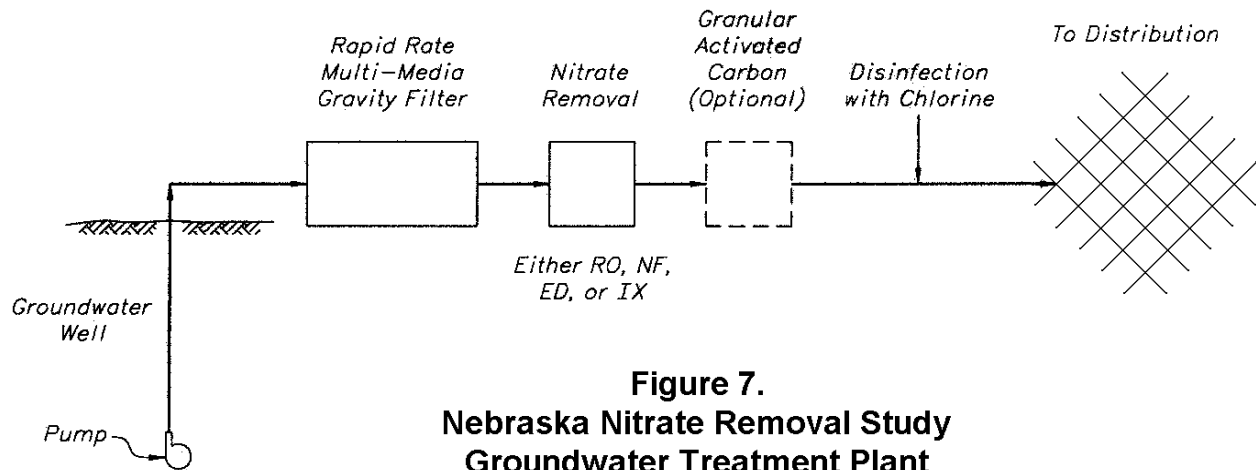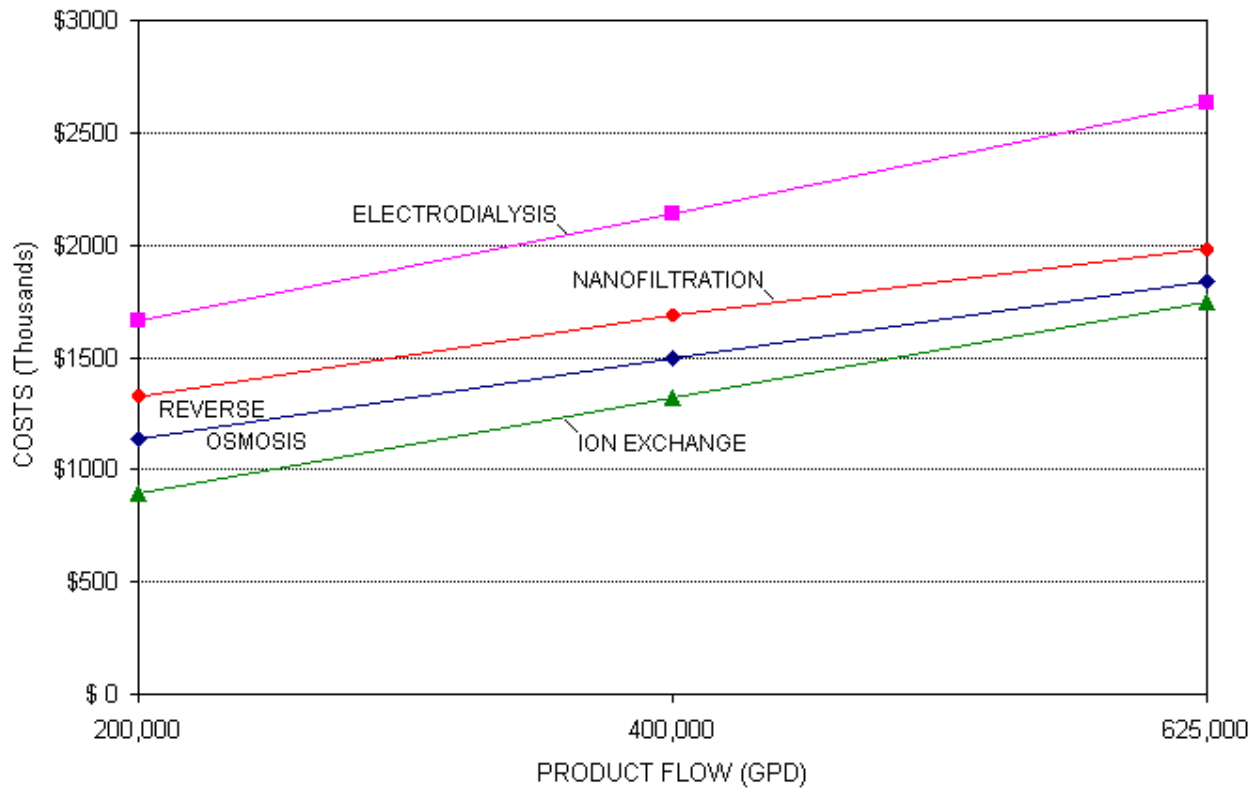
**Figure 7.
Nebraska Nitrate Removal Study
Groundwater Treatment Plant**

Ion Exchange

Costs for IX include an NO_3^- specific resin, a pressure vessel sized for a 100 percent bed expansion, a regenerant storage tank, and a regeneration/backwash pump .

Reverse Osmosis

Costs for RO are based on using 8-inch diameter membranes, rack-mounted, in a 2:1 array of pressure vessels. A variable speed feed pump and pretreatment chemicals of acid, caustic, antiscalant, and a disinfectant are also included. Blending a portion of the RO treated water with filtered water will achieve the required water quality and quantity. An overall recovery rate of 85 percent is assumed.

Nanofiltration

Costs for NF are based on using 8-inch diameter membranes, rack-mounted, in a 2:1 array of pressure vessels. A variable speed feed pump and pretreatment chemicals of acid, caustic, antiscalant, and a disinfectant are also included. Blending a portion of the NF treated water with filtered water will achieve the required water quality and quantity. An overall recovery rate of 85 percent is assumed.

Electrodialysis

Costs for ED assume a 50 percent reduction in flow and a 50 percent rejection of NO_3^- ion per stage. To achieve a 75 percent recovery, two stages are required.

Ex- and In-Situ Denitrification

For both ex-situ and in-situ denitrification, cost data are either very limited, or not available, largely because these processes have not been developed much beyond the lab and pilot testing phases. In Europe, where biological denitrification

Point of Use

Under sink RO units range in price from $500 to $850. Counter top RO units cost between $350 and $500. Counter top distillation units range in price from $150 to $430. The average price for a POU IX unit is about $1,000, but this price varies dramatically depending on installation and water quality.

Relative Operation and Maintenance Costs

O&M costs are updated for electrical energy costs, maintenance materials, chemicals, and labor. Chemical costs are estimated from recent contacts with chemical supply companies or from a chemical periodical. Labor has been estimated at $25.00 per hour and the cost of electricity at $0.06/kW-hr.

Annual O&M costs for a groundwater treatment plant are presented in Table 2. Figure 8 is a graph of the complete treatment annual O&M costs (without granular activated carbon (GAC)) versus flow for RO, NF, ED, and IX, and is based on a NO_3^- concentration of 15 mg/L. Costs for GAC are presented in Table 2, for those sites where herbicides and pesticides (Alachor and Atrazine) may be prevalent due to agricultural practices.

Ion Exchange

Annual O&M costs includes regeneration every 14 days, maintenance material, power, and labor.

Table 2.
GROUNDWATER TREATMENT – ANNUAL O&M COSTS
[Assuming nitrate content of 1,000 mg/L in source water.
GAC = granular activated carbon]

Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Reverse Osmosis	$346,000	$371,000	$398,000
Dual media gravity filter	$25,179	$27,108	$29,100
Chlorine disinfection	$12,691	$12,920	$13,172
TOTAL w/o GAC	$383,870	$411,028	$440,272
GAC	$87,972	$126,972	$160,812
TOTAL w/GAC	$471,842	$538,000	$601,084
Nanofiltration	$318,060	$331,172	$336,552
Dual media gravity filter	$25,179	$27,108	$29,100
Chlorine disinfection	$12,691	$12,920	$13,172
TOTAL w/o GAC	$355,930	$371,200	$378,824
GAC	$87,972	$126,972	$160,812
TOTAL w/GAC	$443,902	$498,172	$539,636
Electrodialysis	$200,000	$278,000	$350,000
Dual media gravity filter	$25,179	$27,108	$29,100
Chlorine disinfection	$12,691	$12,920	$13,172
TOTAL w/o GAC	$237,870	$318,028	$392,272
GAC	$87,972	$126,972	$160,812
TOTAL w/GAC	$325,842	$445,000	$553,084
Ion Exchange	$22,900	$40,000	$59,400
Dual media gravity filter	$24,870	$26,554	$28,293
Chlorine disinfection	$12,691	$12,920	$13,172
TOTAL w/o GAC	$60,461	$79,474	$100,865
GAC	$87,972	$126,972	$160,812
TOTAL w/GAC	$148,433	$206,446	$261,677

Figure 8. Groundwater Treatment — Annual O&M Cost vs. Flow
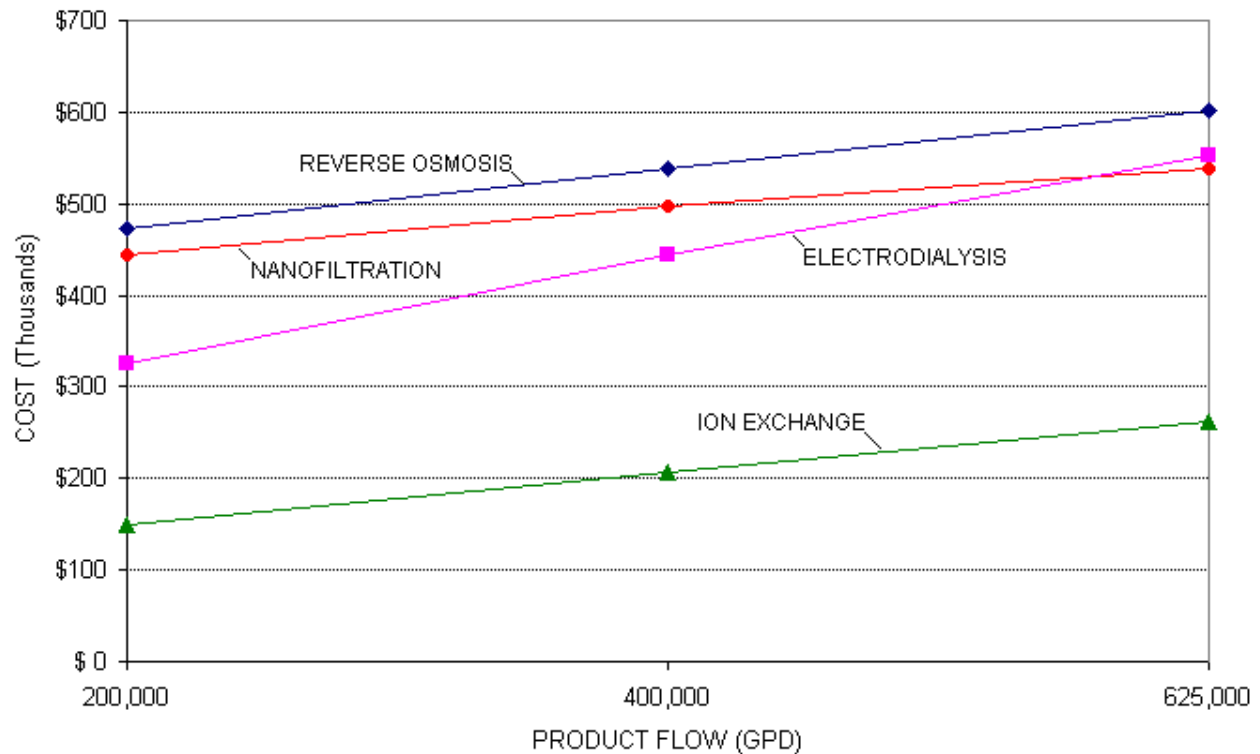
Reverse Osmosis

Annual O&M costs include membrane replacement every three years, power, labor, chemicals, cartridge filters, insurance and lab testing fees. RO membranes were assumed to cost $700 each. Chemicals include antiscalant, chlorine, and cleaning chemicals.

Nanofiltration

Annual O&M costs include membrane replacement every three years, power, labor, chemicals, cartridge filters, insurance and lab testing fees. NF membranes were assumed to cost $1332 each. Chemicals include antiscalant, chlorine, and cleaning chemicals.

Electrodialysis

Annual O&M costs include maintenance material, power, labor, and membrane replacement every 15 years.

Ex- and In-Situ Denitrification

No data available.

Point of Use

RO pre- and post-filters and the RO semipermeable membrane replacement will be proportional to the impurities in the water, but can be estimated at annually. Replacement RO membranes cost between $45 to $235 and pre- and post-filters start at $25. Annual upkeep costs would range between 10 to 36 cents per gallon of drinking water.

The cost of producing a gallon of distilled water ranges from 20 to 40 cents per gallon because electrical costs vary across the country.

An IX water softener doesn't require much maintenance beyond the periodic replacement of salt. Salt is fairly inexpensive throughout the country at about 11 cents per pound.

Amortized Costs and Economics of Scale

Amortized Costs of IX, RO, NF, and ED. — To compare these various technologies' construction and O&M costs, a cost evaluation is necessary that includes the cost over the life of the project and the cost of interest. A life cycle cost analysis has been performed for the BAT processes of IX, RO, NF and ED, using a 20 year economic evaluation period and interest at 7 percent. The results of this amortized cost comparison is shown in Table 3 and Figure 9. Based on the assumptions made in this report, and for raw water sources where there are not many competing anions, IX appears to be the least costly BAT to remove NO_3^- from drinking water.

Economics of Scale. — Economics of scale implies that at larger flows, unit costs for construction and O&M are cheaper than at smaller flows. This is evident by reviewing the amortized costs for the flows presented in this report as shown in Table 3 and Figure 9.

In addition, and as a check for reasonableness of the costs presented herein, Table 4 compares amortized costs at 7 percent interest and 20 years for NF plants in Florida ranging from 1 to 15 MGD (Bergman, May 1996).

Advantages and Disadvantages of Each Alternative

Ion Exchange

Advantages. —
- Ease of operation; highly reliable
- Lower initial cost; resins will not wear out with regular regeneration
- Most effective and most efficient; widely used
- Suitable for small and large installations

Disadvantages. —
- Does not completely eliminate all NO_3^-
- IX cannot remove nonionic dissolved species or microbes
- Requires frequent monitoring for nitrate removal
- Requires salt storage
- Strongly basic anion resins are susceptible to organic fouling; reduced life; thermodynamically unstable

Table 3.
GROUNDWATER TREATMENT – AMORTIZED COSTS PER 1,000 GALLONS OF PRODUCT
[Assuming nitrate content of 1,000 mg/L in source water. GAC = granular activated carbon]

Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Reverse Osmosis	$5.43	$2.96	$2.06
Dual media gravity filter	$0.63	$0.38	$0.28
Chlorine disinfection	$0.20	$0.10	$0.07
TOTAL w/o GAC	$6.27	$3.45	$2.42
GAC	$1.66	$1.20	$0.98
TOTAL w/GAC	$7.94	$4.65	$3.39
Nanofiltration	$5.30	$2.82	$1.85
Dual media gravity filter	$0.63	$0.38	$0.28
Chlorine disinfection	$0.20	$0.10	$0.07
TOTAL w/o GAC	$6.14	$3.30	$2.21
GAC	$1.66	$1.20	$0.98
TOTAL w/GAC	$7.80	$4.51	$3.18
Electrodialysis	$4.11	$2.74	$2.18
Dual media gravity filter	$0.63	$0.38	$0.28
Chlorine disinfection	$0.20	$0.10	$0.07
TOTAL w/o GAC	$4.95	$3.23	$2.54
GAC	$1.66	$1.20	$0.98
TOTAL w/GAC	$6.61	$4.43	$3.51
Ion Exchange	$0.71	$0.60	$0.55
Dual media gravity filter	$0.61	$0.36	$0.27
Chlorine disinfection	$0.20	$0.10	$0.07
TOTAL w/o GAC	$1.53	$1.07	$0.89
GAC	$1.66	$1.20	$0.98
TOTAL w/GAC	$3.19	$2.27	$1.87

Assumptions: 20 year study period, 7% interest rate, and 0.0944 capital recovery factor.

Figure 9. Groundwater Treatment — Amortized Costs vs. Flow
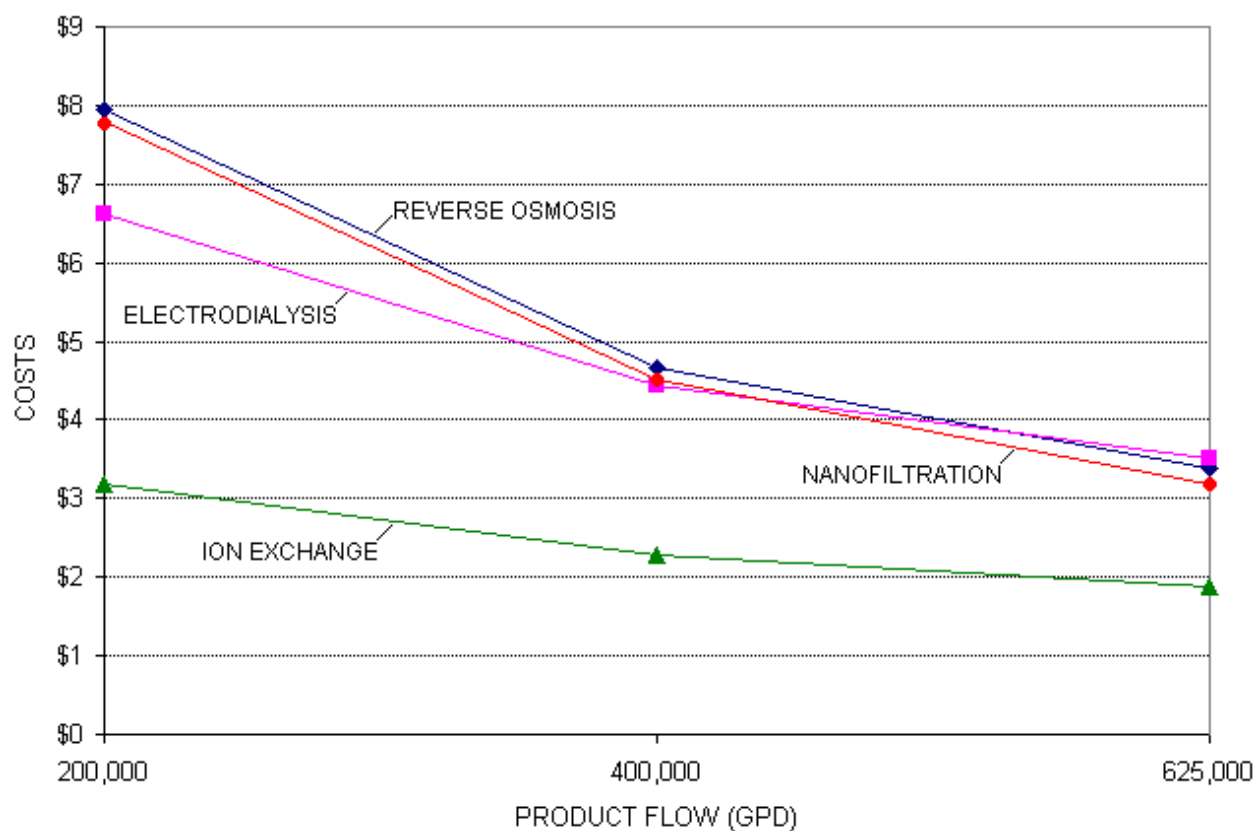
Table 4.
ECONOMY OF SCALE FOR NANOFILTRATION
PLANTS

NF Plant Product Flow	Estimated Average Production Cost Per 1000 gallons
1 MGD	$2.70
5 MGD	$1.04
10 MGD	$0.82
15 MGD	$0.73

Reverse Osmosis

Advantages. —
- Produces highest water quality
- Can effectively treat wide range of dissolved salts and minerals, turbidity, health and aesthetic contaminants, and certain organics; some highly-maintained units are capable of treating biological contaminants
- Low pressure (<100 psi), compact, self-contained, single membrane units are available for small installations

Disadvantages. —
- Relatively expensive to install and operate
- Frequent membrane monitoring and maintenance; monitoring of rejection percentage for NO_3^- removal
- Pressure, temperature, and pH requirements to meet membrane tolerances. May be chemically sensitive

Nanofiltration

Advantages. —
- Can pass more water at lower operating pressures than RO
- Can effectively treat wide range of dissolved salts and minerals, turbidity, health and aesthetic contaminants, and certain organics; some highly-maintained units are capable of treating biological contaminants
- Low pressure (<100 psi), compact, self-contained, single membrane units are available for small installations

Disadvantages. —
- Less expensive to install and operate than RO, and commercially available modules are competitive cost-wise with conventional treatment processes for small systems
- Frequent membrane monitoring and maintenance; monitoring of rejection percentage for NO_3^- removal
- Pressure, temperature, and pH requirements to meet membrane tolerances; may be chemically sensitive

Electrodialysis

Advantages. —
- EDR can operate without fouling or scaling, or chemical addition; suitable for higher TDS sources
- Low pressure requirements; typically quieter than RO
- Long membrane life expectancy; EDR extends membrane life and reduces maintenance

Disadvantages. —
- EDR can operate without fouling or scaling, or chemical addition; suitable for higher TDS sources
- ED cannot remove nonionic dissolved species or microbes
- Not suitable for high levels of Fe and Mn, H_2S, chlorine, or hardness.
- Limited current density; current leakage; back diffusion
- At 50 percent rejection of TDS per pass, process is limited to water with 3000 mg/L TDS or less

Ex-Situ Denitrification

Advantages. —
- Removal is specific for nitrate
- Produce little waste products
- Little mechanical equipment to operate and maintain
- .Competitive costs

Disadvantages. —
- Requires post treatment to remove low dissolved oxygen, bacteria, organics, and residual carbon
- Limited available data to prove track record
- Requires special consideration by State Health.
- Post treatment must include reliable disinfection to remove unwanted pathogens.

In-Situ Denitrification

Due to the limited use of in-situ dentrification, advantages and disadvantages were not investrigated.

Point of Use

RO Advantages. —
- Economical
- Uses no energy
- Removes high levels of dissolved solids
- Uses existing water pressures from 40 to 100 psi
- Quality systems may be employed on virtually any source

RO Disadvantages. —
- They work slowly and stay on all the time
- Slow production requires large holding reservoir
- Removes minerals
- Requires drain to flush away impurities
- Requires pre- and post-filters to be efficient
- Hot water use will damage fragile RO membranes
- Expensive system to maintain
- Requires a technician to install and service
- Wastes water
- Water is flat and has little or no life to it
- Systems are usually large and bulky

Distillation Advantages. —
- Removes most impurities from water including viruses
- Less expensive than bottled distilled water

Distillation Disadvantages. —
- Best suited for municipal water; rural waters of high mineral content will cause excessive scaling and increase maintenance
- Receiving containers may be contaminated again
- Regular cleaning and de-scaling of the elements of the boiler are required
- Produces flat tasting water devoid of all minerals
- Expensive to purchase and maintain
- System is large and bulky, and not portable
- Slow production of water (water must be stored) meaning that without careful planning, water could run out

IX Advantages. —
- Improves water quality by softening water
- Enhances removal of heavy metals, nitrates, and sulfates

IX Disadvantages. —
- Must use additional filters to remove bacteria, sediment, chlorine, and organics
- Requires constant checking to maintain efficiency
- Bacterial growth in resin bed presents major health concerns
- Needs electronic monitoring devices
- Backwashing required to be effective in the exchange process
- Most older systems left elevated levels of sodium in the water

TREATMENT OF SURFACE WATER

Some communities in Nebraska are located near a reliable surface water source and may consider substituting all or part of their groundwater supply with surface water. Surface water is usually more difficult to treat than groundwater primarily as a result of fluctuating turbidity and suspended solids, and in the case of Nebraska the presence of herbicides and pesticides from runoff from agricultural drainage, bacteria, and DBPs. The EPA has passed the Surface Water Treatment Rule (SWTR) for surface water, part of which mandates proper filtration and disinfection for turbidity and DBPs. A schematic of a typical surface water treatment plant, that would achieve SWTR compliance for most of the surface water qualities in Nebraska, is shown in Figure 10.

For surface water treatment, costs assume that alum or polymer will be needed for episodically high suspended solid sediment. Surface water treatment also includes a solids contact reactor (SCC). An SCC is one treatment unit which combines the unit operations of rapid and slow mixing and clarification. The SCC is followed by a rapid rate, dual media (sand and anthracite)
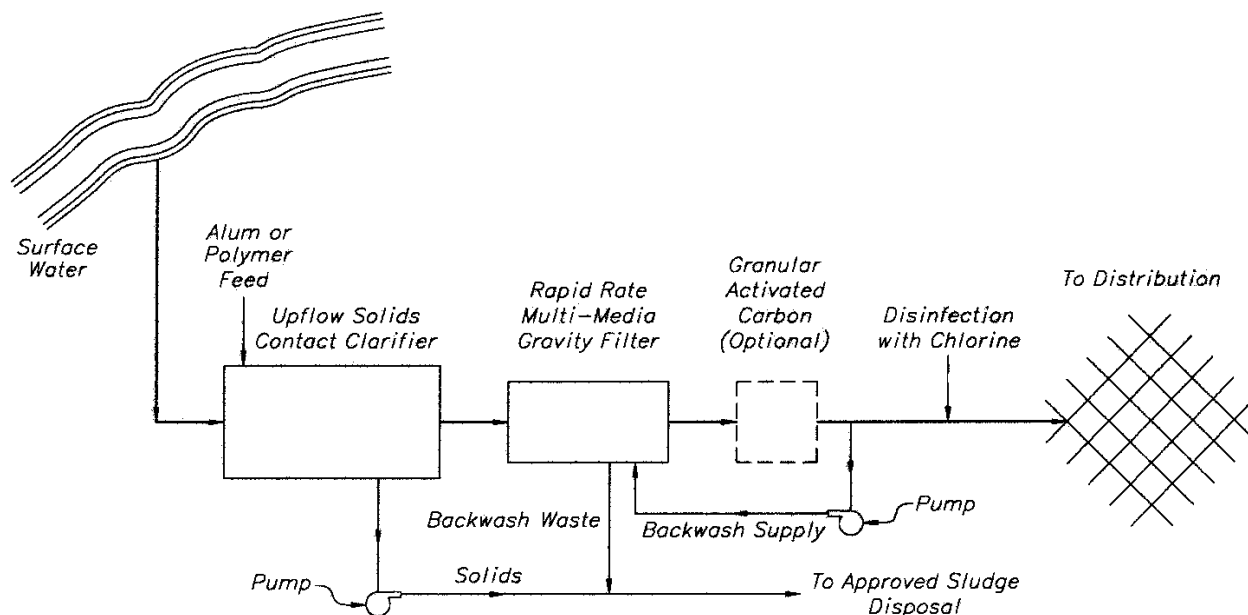
**Figure 10. Nebraska Nitrate Removal Study
Surface Water Treatment Plant**

gravity filter, and post-disinfection using chlorine. The episodically high levels of suspended solids will require careful sizing of the filter. The estimates contain a conservative filter size based on surface loading rate (SLR) of 5 gallons per minute per square foot. This SLR may be too small for locations with known extremely high suspended solids levels. Gaseous chlorine from cylinders is assumed at a feed rate of 3 mg/L.

Construction, annual O&M, and amortized costs for a typical surface water treatment plant are summarized in Table 5 and in Figures 11, 12, and 13, for flows from 200,000 to 625,000 GPD.

CONNECTING TO OR EXPANDING EXISTING WATER SYSTEMS

Components

The specific components and final design associated with connection to an existing WTP are based on the exact numbers and types of connections, their distance from the WTP, and their elevation in relation to the WTP. Typically, the following major and minor components can be expected:

Major components:
- raw water well(s), where existing volume is not adequate to supply new customers
- water treatment capacity, where existing treatment is not adequate to supply new customers
- storage tank(s), where existing volume is not adequate to supply new customers

Table 5.
SURFACE WATER TREATMENT – CONSTRUCTION, O&M, AND
AMORTIZED COSTS
[GAC =granular activated carbon]

CONSTRUCTION COST			
Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Polymer addition	$39,891	$40,288	$40,742
Upflow solids contact clarifier	$149,888	$156,152	$163,198
Dual gravity filtration	$209,295	$282,554	$350,058
Chlorination	$24,400	$26,163	$27,904
TOTAL w/o GAC	$423,474	$505,157	$581,902
Granular activated carbon	$355,141	$516,508	$657,381
TOTAL w/GAC	$778,615	$1,021,665	$1,239,283

ANNUAL O & M COST			
Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Polymer addition	$10,800	$14,653	$18,989
Upflow solids contact clarifier	$13,117	$13,294	$13,493
Dual gravity filtration	$24,870	$26,554	$28,293
Chlorination	$12,867	$13,261	$13,692
TOTAL w/o GAC	$61,654	$67,762	$74,467
Granular activated carbon	$87,972	$126,972	$160,812
TOTAL w/GAC	$149,626	$194,734	$235,279

AMORTIZED COST PER 1000 GALLONS OF PRODUCT			
Treatment Process	Product Flow (GPD)		
	200,000	400,000	625,000
Polymer addition	$0.20	$0.13	$0.10
Upflow solids contact clarifier	$0.37	$0.19	$0.13
Dual gravity filtration	$0.61	$0.36	$0.27
Chlorination	$0.21	$0.11	$0.07
TOTAL w/o GAC	$1.39	$0.79	$0.57
Granular activated carbon	$1.66	$1.20	$0.98
TOTAL w/GAC	$3.06	$1.99	$1.54

Assumptions: 20 year study period; 7% interest rate; and 0.0944 capital recovery factor.

- booster station(s), where existing pressure is not adequate to supply new customers
- distribution system pressure mains from the existing system connection(s) to each home or connection
- air relief valves housed in concrete basins at high points in the water piping to release trapped air

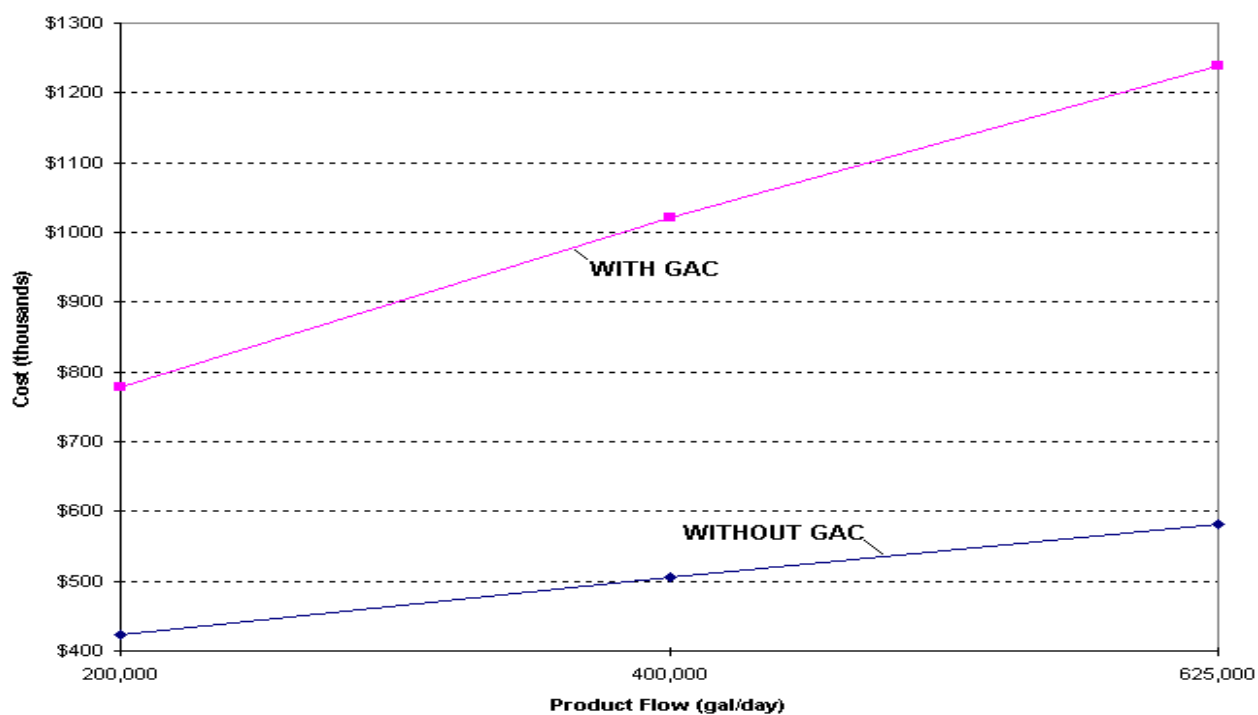Figure 11. Surface Water Treatment Construction Cost vs. Flow

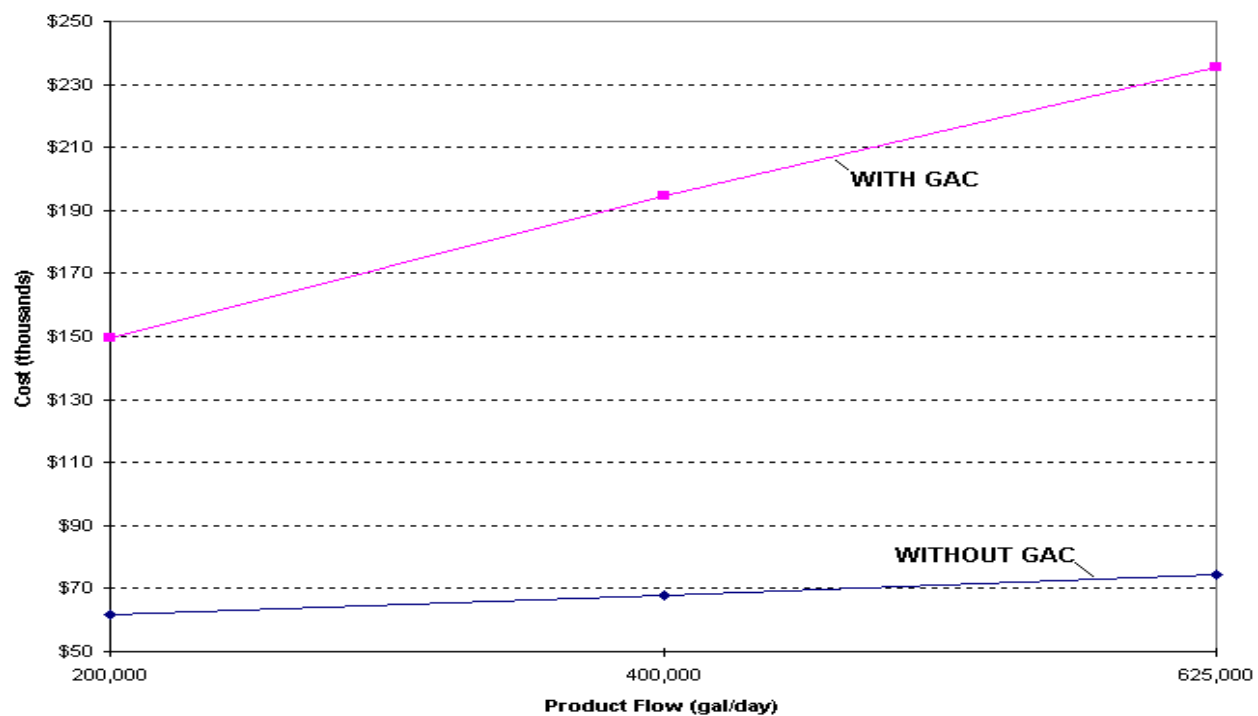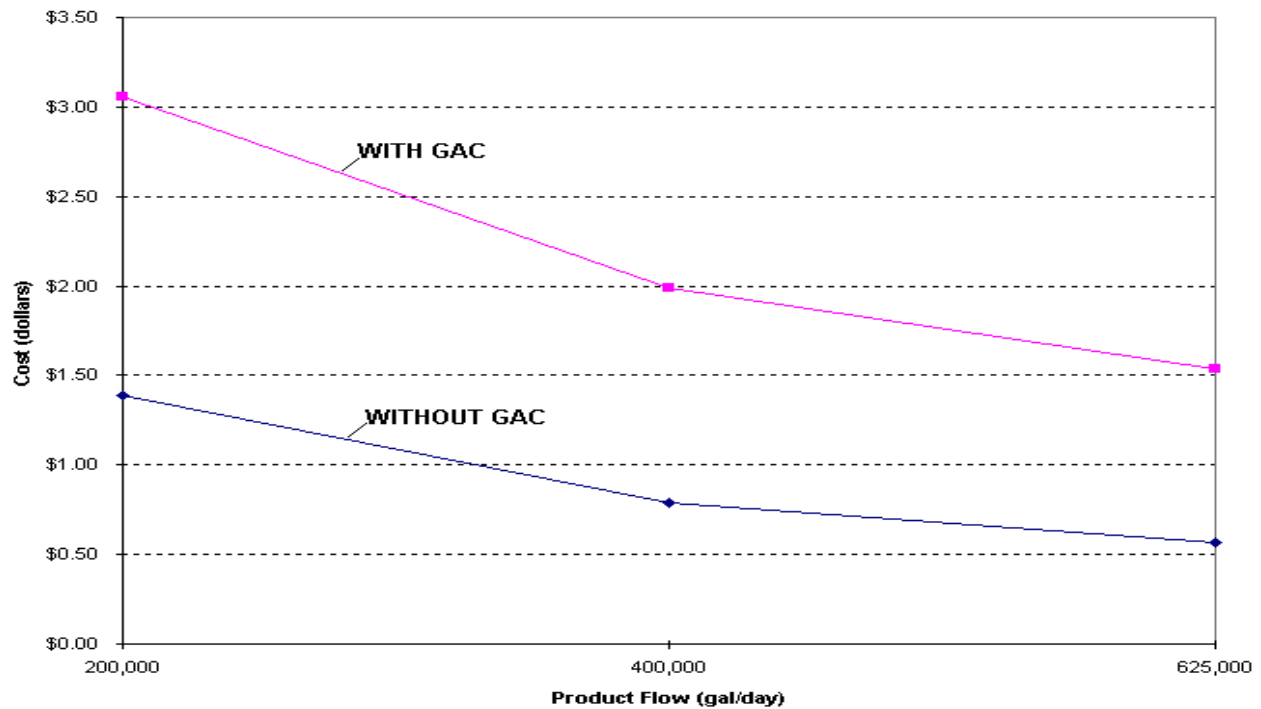Figure 12. Surface Water Treatment – Annual O&M Cost vs Flow

Figure 13. Surface Water Treatment – Amortized Cost vs. Flow

Minor components:
- piping, fittings, and valves to homes or connections of sizes and materials suitable for the installation
- flow meter at each home or connection for measuring the flow of sizes suitable for the installation
- 4-way expansion joints at connections to accommodate minor deflections in the pipe
- detectable warning tape coded for water system piping installed above all pipe lines

Assumptions

The following assumptions have been used to quantify a typical connection to an existing WTP:

Average daily flow (ADF):	125 GPCD
Maximum day water use:	2:1 ADF
Peak daily flow:	3:1 ADF
Safe well yields:	Varies, based on aquifer

Treatment capacity:	Based on ADF
Storage Requirement:	Maximum day plus fire flow plus equalization
Fire Flow:	1500 GPM for 2 hours
Equalization:	2

Costs

The specific costs associated with connection to an existing WTP are based on the above components and assumptions. Confirmation of the above assumptions plus additional criteria such as distance to the WTP, typical well development costs and yeilds, and materials of construction for storage tanks are required before this section can be finalized.

RECOMMENDATIONS

This report recommends that consideration be given to centralized treatment to reduce the number of treatment plants and associated costs due to economies of scale.

In addition, when the groundwater quality in a small town in Nebraska contains high levels of nitrates, but other contaminants are below the SDWA MCLs, the community should consider ion exchange water treatment.